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CDF and DØ

Search for New Particles in Multijet Final States at the Tevatron

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**SEARCH FOR NEW PARTICLES
IN MULTIJET FINAL STATES AT THE TEVATRON**

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Abstract

We present the latest results of the searches for new particles in hadronic final states performed in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV.

The large data samples collected with the CDF and D0 detectors at the Tevatron collider between 1992 and 1995 allow searches for low cross section phenomena in dijet and multijet events, despite the hindrance of the high background from normal QCD processes. However, no signal for new physics is found, and the data show good agreement with QCD. Limits on the mass and on the cross section of the searched states can thus be set.

1 Introduction

Ever since the discovery of the W and Z bosons with the UA1 and UA2 detectors in 1983, proton–antiproton colliders have proven to be successful probes for new physics in the high energy domain. The high rates and high collision energies achievable in these environments have pushed our understanding of the strong interactions and of particle physics in general to farther and farther horizons. The usefulness of hadronic probes in particle interactions has however always come together with an enormous complexity of the final states, as compared with the clean, easily understandable and manageable physics electron-positron colliders can provide. But leptons are not only a guarantee for a clean interaction when they collide: they have always been thoroughly exploited as a unmistakable signal for high interest phenomena when they show up in the detectors. $p\bar{p}$ colliders currently use high P_T leptons as the best way to trigger and to tag particle decays as W and Z bosons, heavy quarks like charm, bottom and top, and to search for supersymmetry and new phenomena.

New physics searches in the zero lepton final states are a hard thing to manage. One may just compare the production cross section of a pair of jets with 30 GeV of transverse energy –which is in the microbarns ballpark at the Tevatron– with the same final state caused by the decay of a W or Z boson, which lies in the few nanobarns domain: this example may give the idea of the hard times one usually faces when trying to use these final states for new particle searches.

Notwithstanding the low signal/noise ratio, a vector boson signal has been published in 1987 by the UA2 collaboration¹. For many years since then no other resonances in jet final states have shown up in hadronically triggered data samples at $p\bar{p}$ colliders. But things are rapidly changing now: the CDF collaboration has used a multijet data sample to observe the six jet decays of the $t\bar{t}$ pairs (see fig.1); and another CDF analysis to be submitted to *Physics Review Letters* has recently shown how a clean $W \rightarrow jj$ peak can be extracted from a sample enriched in $t\bar{t}$ decays (see fig.2).

The new collider run at the Tevatron, starting in 1999, will hopefully exploit the advantageous branching ratios of hadronic decays of many new states to push still further their searches: the next millennium will probably start with Tevatron and LHC showing how jets can be very effective in reconstructing the event decay kinematics when TeV physics comes into play.

2 Jets with the CDF and D0 Detectors

The CDF and D0 collaborations have put a considerable effort in designing and building detectors that could measure with sufficient precision jet energies in the largest possible solid angle, being aware of the importance of these measurements for both QCD studies and for the reconstruction of high mass decays like that of top quark pairs.

Both detectors come equipped with calorimeters, divided in inner electromagnetic sections and larger outer portions designed for complete containment of hadronic showers; and both are physically divided into sections that cover different ranges of pseudorapidity, up to $|\eta| \simeq 4$. CDF features a central scintillator-based calorimeter and forward-backward symmetric devices where a Argon-Ethane gas mixture is the active medium; the segmentation geometry in $\eta - \phi$ space is $0.1 \times (0.09 \div 0.27)$, and the stochastic resolution term is $\sigma_E/E = 14\%/\sqrt{E}$ for electrons, and $\sigma_E/E = 75\%/\sqrt{E}$ for hadrons.

¹*Phys. Lett.* 186B (1987), 452. The search was later updated with a larger data sample which produced a signal of 5367 ± 958 events: *Z. Phys.* C49 (1991), 17.

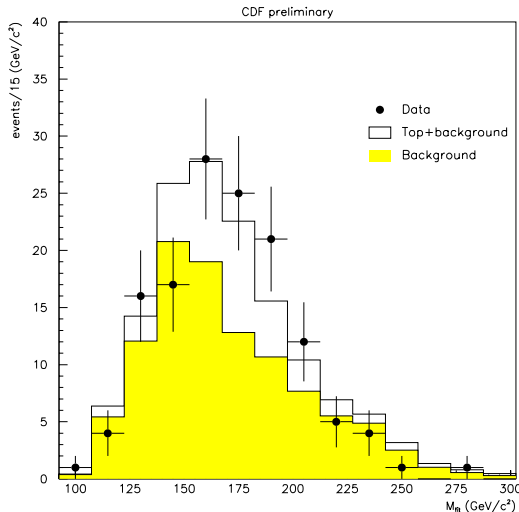


Figure 1: *Reconstructed mass of the top quark from events with six jets. The black dots are data, the shaded histogram is the expected background contribution, and the white histogram is the sum of background and $t\bar{t}$ contributions.*

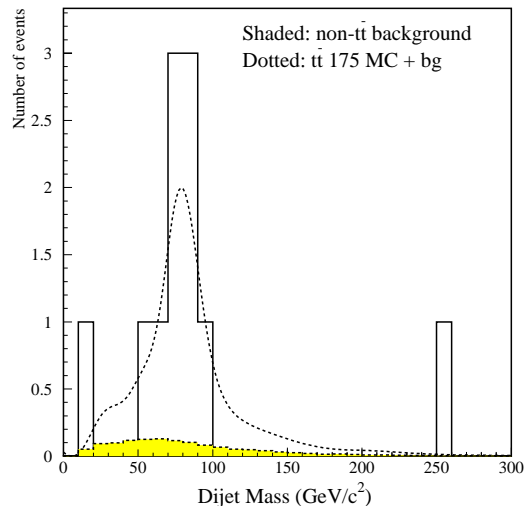


Figure 2: *The dijet mass distribution for events with an electron or muon, missing transverse energy, and two more jets both coming from b decay. The 11 events are compared to background expectations alone (shaded) and to background plus $t\bar{t}$.*

D0 features a uniform design of depleted Uranium and liquid Argon calorimetry both for the central region and for the two endcap detectors. The calorimeter segmentation is 0.1×0.1 in most of the detector components, but is finer in the third layer of the electromagnetic sampling section (0.05×0.05), the one where e.m. showers approach their maximum development. For electrons the resolution is $\sigma_E/E = 15\%/\sqrt{E}$, and for hadrons is about $\sigma_E/E = 50\%/\sqrt{E}$.

To trigger on jet events, both experiments rely on many single cluster triggers, hardwired with different energy thresholds. The lower energy triggers have to be heavily prescaled in order to keep the rate of event collection matched with data storage capabilities. Both collaborations have also designed multijet triggers able to collect events with four or more jets, and triggers based on the sum of transverse energy in the entire calorimeter.

To reconstruct jets offline, both D0 and CDF use cone-based algorithms that fulfil the Snowmass conference standards². The jet radius is normally chosen to be $R=0.7$, a value considered to be the best compromise between the reduction of underlying event background and the minimization of out-of-cone losses, and the most stable with regards to theoretical calculations.

The algorithms devised for jet identification compile lists of towers over a 1 GeV threshold in transverse energy, and then form circles around them, evaluate the center of gravity of the energy distribution inside the circles, and displace them to those positions; the procedure is repeated until stability is achieved. Jet merging is decided if two neighboring jets share more than a certain fraction of the lower energy jet (50 % at D0, 75% at CDF).

The jet energies have to be carefully corrected before being useful for mass bump searches. CDF uses a two step procedure to accomplish that: first, a detector response function is used to take care of nonlinearities and of possible energy losses at detector boundaries; after that,

²J.Huth et Al. in "Research Directions for the decade" Proceedings of the summer study on High energy Physics, Snowmass, Colorado, 1990, ed. E.L.Berger (World Scientific,1991).

an absolute energy scale correction is evaluated with the help of Monte Carlo simulations, to take into account out-of-cone losses, and to correct for underlying event contributions to the energy flow inside the cones, low response of the calorimeter to hadrons, and other effects. A systematic error on the jet energy scale can then be evaluated by using Z+1 jet data, where the Z is well measured through its leptonic decay and has to balance in P_T the jet. The D0 collaboration sets first the absolute jet energy scale in the e.m. compartments, with the aid of Z decay electrons, and then uses photon+jet events to get the response function for the jet in the hadronic compartments. After the corrections, both collaborations estimate the uncertainty on the jet energy scale at the 5 % level.

An important feature of the CDF detector is its ability to identify b quark decays by reconstructing their decay vertex, thanks to a very precise Silicon Vertex detector (SVX) capable of a $\sim 15\mu m$ impact parameter resolution for charged tracks. The D0 detector can also tag b quark decays by identifying low P_T muons in the jet cones; this method is however limited by the branching ratio for semileptonic decays and by the muon identification efficiency.

3 Heavy Neutral Scalar Searches in Four Jet Events

At the Tevatron, associated production is predicted to be the most promising process for a search of neutral scalar particles, such as the long hunted Higgs boson or new states predicted by the MSSM or by technicolor models introduced as alternative scenarios for electroweak symmetry breaking, such as light color singlet technipions³.

The most promising signature for these processes consists in a charged lepton plus some missing transverse energy due to an undetected neutrino –both from W decay– accompanied by a pair of jets originated from the b quarks the new particle has decayed to. Both D0 and CDF have searched in this channel. These searches have been flanked at CDF by a study of four jet events, to look for both the W and the H bosons in the dijet final state. The high background from QCD processes can be substantially reduced with the request that two of the four jets in the event come from b decay.

By studying the invariant mass distribution of the b jet pairs, CDF has put a new limit on the cross section for associated WH production (see fig.3). For a detailed description of this search the reader is referred to the writeup of Leslie Groer's talk in these proceedings.

4 Dijet Bump Searches

Many extensions to the Standard Model predict the existence of new states which may decay to a pair of jets. These include axigluons, excited quarks, color octet technirhos, W' and Z' bosons, and E_6 diquarks. These states can be searched for in events with two jets by computing the dijet mass and comparing it with background predictions: the absence of bumps in the spectrum may be turned into cross section limits.

4.1 Searches at D0

To search for excited quarks in the process $qg \rightarrow q^* \rightarrow qg$, and for new gauge bosons W' and Z', the D0 collaboration uses data collected with its four single jet triggers. The data samples, featuring E_T thresholds at 30, 50, 85 and 115 GeV, correspond for the 1994-95 data taking to integrated luminosities of 0.355, 4.56, 51.7 and 90.7 pb^{-1} , respectively.

³See for instance the paper by Eitchen, Lane and Womersley, HEP-PH/9704455.

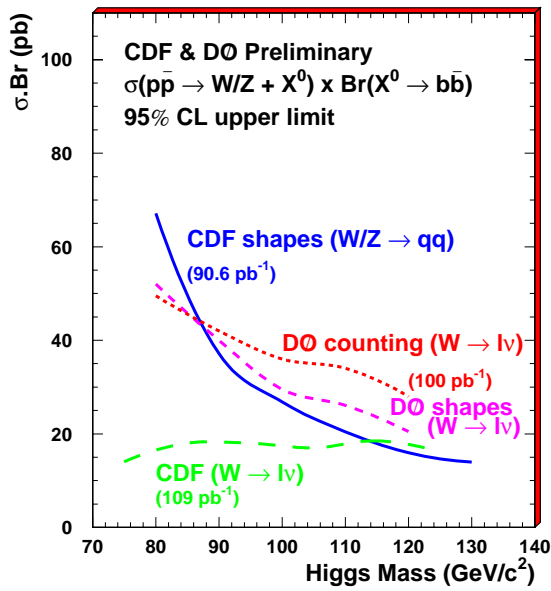


Figure 3: The various cross section limits obtained by D0 and CDF for the WH production.

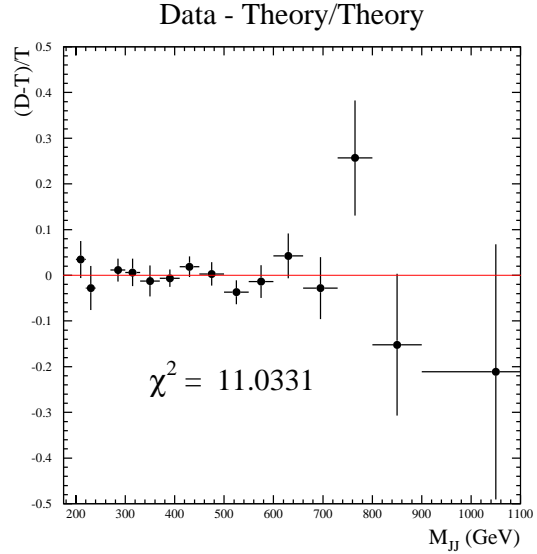


Figure 4: The residuals of the fit of the dijet mass spectrum with the QCD distribution obtained with JETRAD.

A removal of isolated noisy calorimeter cells, accelerator losses, cosmic ray background and pileup events is performed with quality cuts; after the removal the residual background contamination is less than 2 % for jets with E_T lower than 500 GeV. For each event that passes the selection, a dijet invariant mass can be calculated. The events are weighted by the efficiency of the quality cuts applied. To enhance the S/N ratio for new particles over the QCD background, the pseudorapidity of the first two jets is required to lie in the interval $|\eta| < 1.0$, and their difference has to be $|\eta_1 - \eta_2| < 1.6$. The relative normalizations of the four datasets are established by requiring equal cross sections in the regions where they overlap. The four datasets are used above mass thresholds of 200, 270, 370 and 500 GeV, where they are fully efficient.

From the mass spectrum a resonance contribution can be estimated by fitting the data with a QCD continuum distribution obtained with the JETRAD Monte Carlo⁴ and a smearing procedure that takes into account the jet resolution, plus a signal line shape obtained with the PYTHIA Monte Carlo⁵ for excited quarks of a given mass; the fit is performed with the binned maximum likelihood method. The QCD shape alone is able to fit the data well, as can be seen in fig.4. By taking into account the systematic uncertainties in the cross section, coming from the measurements of luminosity (8%), jet energy scale (5%) and data selection cuts (2%), a cross section limit can be obtained (fig.5). It is thus possible to exclude excited quarks with a mass lower than 720 GeV, W' bosons in the range $340 < M_{W'} < 680$ GeV, and Z' bosons in the range $365 < M_{Z'} < 615$ GeV.

4.2 Searches at CDF

To search for new states decaying to a pair of jets, CDF uses data collected with single jet triggers. These have nominal threshold at 20, 50, 70 and 100 GeV, and their effective integrated lu-

⁴W.Giele, E.Glover, D.Kosover, *Phys. Rev. Lett.* **73** (1994), 2019.

⁵H.Bengtsson, T.Sjostrand, *Comp. Phys. Comm.* **46** (1987), 43.

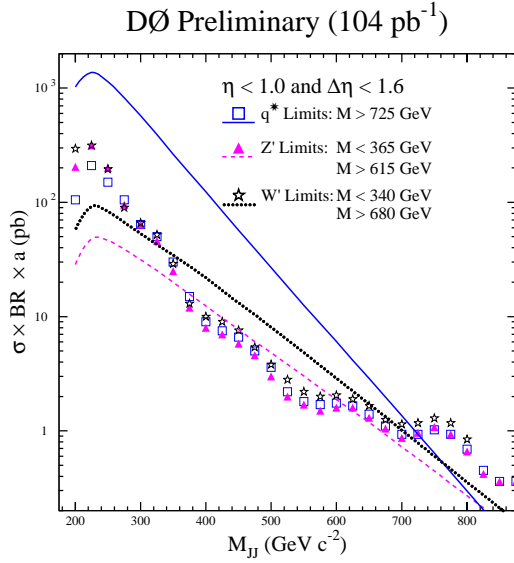


Figure 5: Mass limits obtained for excited quarks and new gauge bosons by the DØ collaboration.

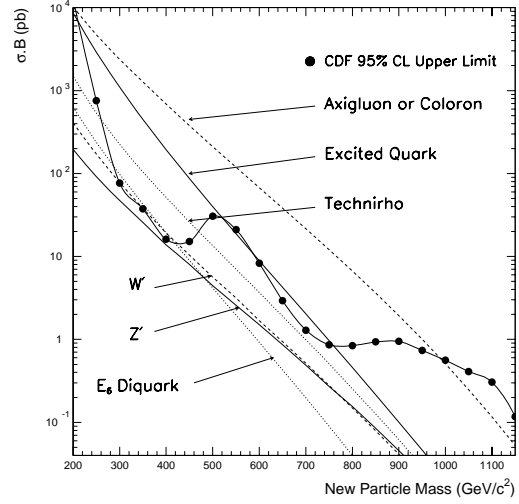


Figure 6: The upper limit on the production cross section times branching ratio of the searched states obtained by the CDF collaboration.

minosity are respectively 0.126, 2.84, 14.1 and 106 pb^{-1} . After jet corrections, the four datasets are used to measure the dijet mass spectrum above 180, 241, 292 and 388 GeV respectively, that is from the point where they become fully ($> 95\%$) efficient. Events are required to have the two more energetic jets inside a pseudorapidity region $|\eta| < 2.0$, their scattering angle in the center-of-mass frame being $|\cos \theta^*| < 2/3$: this provides uniform acceptance as a function of mass while reducing the QCD background. The differential cross section, $d\sigma/dM$, is then plotted versus the mean dijet mass in bins of width approximately equal to the dijet mass resolution ($RMS \sim 10\%$), and fit with a parametrization $d\sigma/dm = A(1 - m/\sqrt{s} + Cm^2/s)^N/m^P$, with four parameters A, C, N, P. This gives an adequate description of the spectrum ($\chi^2/DOF = 1.49$).

In the absence of an excess of events over the fit distribution, which for a new particle would show up in at least two neighboring bins, an upper limit for the cross section of the new particles is extracted by performing a binned likelihood fit of the data to the background parametrization and the mass resonance shape⁶, for 20 values of new particles mass ranging from 200 to 1150 GeV in 50 GeV intervals. By convoluting each of the 20 likelihood distributions with the corresponding total gaussian systematic uncertainty, 95% C.L. upper limits in the cross section are extracted. The systematic uncertainties come from many different sources, the most relevant being the energy scale (5%); their effect is evaluated by varying the source of uncertainty by $\pm 1\sigma$ and refitting the data. From the predicted lowest order production cross sections for the searched particles we can thus extract exclusion intervals in their mass (see fig.6). The exclusion regions are: for axigluons and flavor universal colorons, between 200 and 980 GeV; for excited quarks, between 80 and 570 GeV and between 580 and 760 GeV⁷; for color octet technirhos, between 260 and 480 GeV; for W' bosons, between 300 and 420 GeV, and for E_6 diquarks, between 290 and 420 GeV.

⁶The resonance shape is the same for all the particles considered, since their natural width is predicted to be smaller than the experimental resolution.

⁷Due to a likely statistical fluctuation of the data in the region around 580 GeV, CDF cannot exclude that mass region for excited quarks; that interval is however ruled out by the DØ search.

5 Characterization of Multijet Events

The CDF collaboration has recently published a detailed analysis of events with three, four and five jets, where a set of variables that completely characterize the event kinematics are used to compare the data to QCD predictions and to a phase space model. We review that analysis here, since it can actually be thought of as a search for new physics in multijet final states, and we also discuss a soon-to-be-published analysis of six jet events, performed with the same tools.

5.1 Comparisons of Three, Four and Five Jet Events to QCD Predictions

CDF has studied events with three, four and five jets collected from 1992 to 1995 with a trigger requiring the sum of jet transverse energy to be greater than 300 GeV. Multijet mass distributions and configuration variables have been used to compare the data to a leading order QCD matrix element calculation, a QCD parton shower calculation, and a model where jets are distributed evenly in the N-body phase space.

The leading order QCD predictions were obtained with the NJETS⁸ Monte Carlo program, based on a complete calculation of the LO $2 \rightarrow N$ matrix element. To avoid singularities the program needs as input the minimum separation between the final state partons, which was chosen to be $\Delta R = 0.9$ to match the experimental data; the chosen structure functions were the KMRSD0, with the renormalization scale set at the average P_T of the outgoing partons. The parton energies were then smeared according to the CDF jet energy resolution, $\sigma_E = 0.1E$. The parton shower calculations were done with the HERWIG Monte Carlo⁹, together with a full simulation of the CDF detector response. The structure functions used were the CTEQ1M, and the renormalization scale was set at the value $Q^2 = stu/2(s^2 + t^2 + u^2)$. The phase space model was based on the GENBOD phase space generator¹⁰. Comparisons between phase space distributions and QCD calculations allow an understanding of what are the variables most sensitive to QCD effects in multijet production.

The starting data sample, featuring events with jets with pseudorapidity $|\eta| < 3.0$, with corrected transverse energy $E_T > 20$ GeV, their sum being $\Sigma E_T > 420$ GeV, consists in 30245 events. To completely characterize a N jet event one can devise a set of $(4N-4)$ variables¹¹. The most relevant N jet variable is the total mass of these N jets, and the remaining variables can be reduced by iteratively merging together the two jets with lowest dijet mass, and considering the event to be a N-1 jet event; this procedure can be stopped when three objects remain, where the eight 3-jet variables are well known and used in the literature: the 3-jet mass M_{3j} , the four parameters that specify the relative configuration, X_3 , X_4 , $\cos \theta_3$ and ψ_3 , and three variables that specify the single jet masses, f_1 , f_2 and f_3 . The remaining variables for a 4-jet (four) or a 5-jet (eight) event can then be chosen to be the normalized masses of the two merged jets, the energy fraction of the more energetic of the two merged jets, and the cosine of the angle between the plane containing the resultant jet and the beam and the plane containing the two jets alone before their merging took place.

⁸F.A.Behrends, W.Giele, H.Kuijf, *Nucl. Phys.* **B333** (1990), 120.

⁹G.Marchesini, B.Webber, G.Abbiendi, I.Knowles, M.Seymour, L.Stanco, *Comp. Phys. Comm.* **67** (1992), 465.

¹⁰*CERN Prog. Libr. Man.* 1989.10.03, Rout. W515, 6.503. The generator was provided in input with the single jet mass distributions and the multijet mass distributions predicted with the help of the HERWIG Monte Carlo.

¹¹These variables have been introduced in S.Geer and T.Asakawa, *Phys. Rev.* **D53** (1996), 4793.

Both Monte Carlo programs are seen to be able to reproduce the multijet mass distributions well. For the three jet variables, the most dramatic disagreement between phase space predictions and data is found on the angular distributions in $\cos \theta_3$ and ψ_3 , while QCD predictions are in reasonable agreement with the data. The Dalitz variables X_3 and X_4 are also well reproduced by both QCD Monte Carlos. The single jet masses are slightly overestimated by the HERWIG calculations.

For the four and five jet data the distributions overall show that both QCD calculations are able to reproduce well both the Dalitz and the angular distributions, with a slight superiority of the leading order NJET Monte Carlo. The phase space model is on the contrary unable to reproduce the angular distributions, and fails to describe correctly also some regions of the 4- and 5-jet Dalitz distributions.

From these comparisons, it is possible to see that $2 \rightarrow 2$ scattering plus gluon radiation provides a good first approximation to the full LO QCD matrix element for events with 3, 4 and 5 jets in the final state. The phase space model disagrees most with the data in the regions of parameter space where QCD predicts large contributions to initial and final state radiation.

5.2 Comparison of Six Jet Events to QCD Predictions

An analysis similar to that just described has very recently been completed at CDF by using events with six jets in the final state. The methodology of the comparison is completely equivalent to that just reported for three to five jet events; the differences are the following:

- a slightly different trigger, requiring $\sum E_T > 175$ GeV, has been used to collect the six jet events dealt with here;
- the NJETS LO calculations are exact only with up to five partons in the final states; for $N=6$, NJETS uses an approximation based on neglecting non-LO color contributions¹² and by simplifying the helicity computation with the SPHEL approximation¹³;
- different parametrizations have been chosen for the structure functions: for the HERWIG Monte Carlo the CTEQ2L was used, while for the NJETS Monte Carlo the CTEQ3M was used;
- in order to avoid trigger inefficiency regions of phase space, a higher cut is applied on the total mass of the six jets: $M_{6j} > 520$ GeV.

The data, consisting in 1282 events, shows a good agreement with the QCD calculations on all the 20 variables necessary to fully describe the final state. Many of the distributions are instead very poorly described by the phase space model, particularly where poles are contributing from the QCD multijet matrix element, corresponding to soft and collinear radiation from the incoming and outgoing partons (see for instance figs. 7 and 8).

6 Conclusions

In conclusion, D0 and CDF have found no evidence, in the datasets collected since 1992 at the Tevatron collider, for new physics in multijet final states. Limits have been put on the mass of all searched states, except for the Higgs boson, where only cross section limits are yet possible. The analysis of events with three to six jets in the final state at CDF have shown no hints of deviations from the QCD matrix element.

¹²F.Behrends, W.Giele, H.Kuipf, *Phys. Lett.* **232B** (1989), 266.

¹³For a description see F.Behrends, H.Kuijf, *Nucl. Phys.* **B353** (1991), 59.

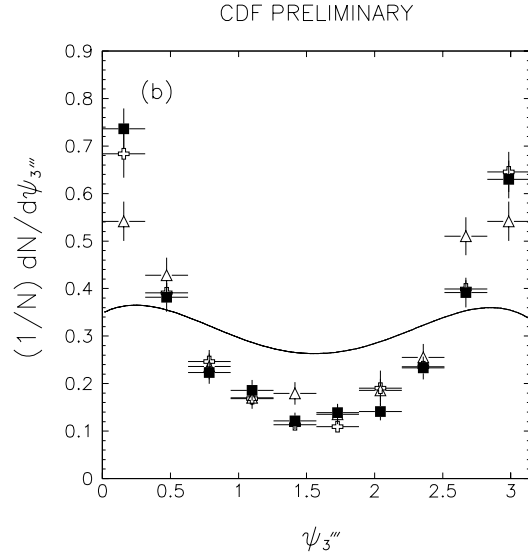


Figure 7: ψ_3 distribution for the data (solid squares) compared to the predictions of HERWIG (triangles), NJETS (crosses) and phase space (smooth line).

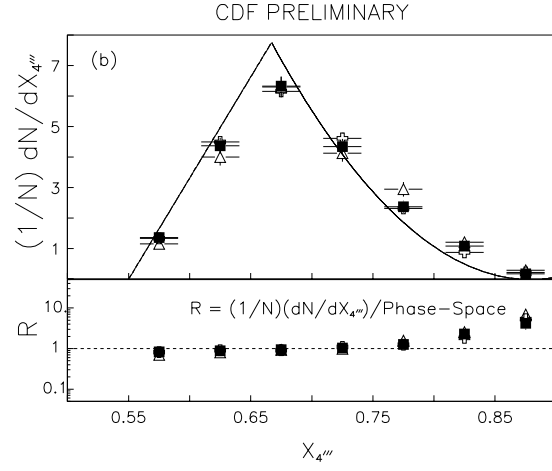


Figure 8: X_4 distribution for the data (solid squares) compared to the predictions of HERWIG (triangles), NJETS (crosses) and phase space (line). The lower section shows the deviations from the prediction of the phase space model.